Large Momenta Fluctuations Of Charm Quarks In The Quark-Gluon Plasma

S. Terranova, D.M. Zhou and A. Bonasera *
Laboratorio Nazionale del Sud,
Istituto Nazionale Di Fisica Nucleare,
Via S. Sofia 44, I-95123 Catania, Italy

We show that large fluctuations of D mesons kinetic energy (or momentum) distributions might be a signature of a phase transition to the quark gluon plasma (QGP). In particular, a jump in the variance of the momenta or kinetic energy, as a function of a control parameter (temperature or Fermi energy at finite baryon densities) might be a signature for a first order phase transition to the QGP. This behaviour is completely consistent with the order parameter defined for a system of interacting quarks at zero temperature and finite baryon densities which shows a jump in correspondance to a first order phase transition to the QGP. The J/Ψ shows exactly the same behavior of the order parameter and of the variance of the D mesons. We discuss implications for relativistic heavy ion collisions within the framework of a transport model and possible hints for experimental data.

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The production of a new state of matter, the Quark-Gluon Plasma (QGP), can be obtained through ultra-relativistic heavy ion collision (RHIC) at CERN and at Brookhaven [1]. QGP can be formed in the first stages of the collisions, and can be studied through the secondary particles produced.

Some features of the quark matter can be revealed by studying the properties of hadrons in a dense medium. The particle J/Ψ is a good candidate because the formation of the QGP might lead to its suppression[2]. Here we want to show that in reality informations about the QGP are carried by the charm quarks. These quarks interact strongly with the surrounding matter and as a result we have a suppression of the J/Ψ, but also large fluctuations of the charm quarks kinetic energies which could be revealed by the D mesons distributions or other charmed mesons or baryons. To see this, we elaborate on a semiclassical model which has an EOS resembling the well known properties of nuclear matter and its transition to the QGP at zero temperature and finite baryon densities already discussed in [3]. We simulate the nuclear matter which is composed of nucleons (which are by themselves composite three-quark objects) and its dissolution into quark matter. In addition, for our system of colored quarks, we will show how the color screening is related to the lifetime of the particle J/Ψ in the medium. In particular, we will see that the lifetime of the J/Ψ as a function of density behaves as an order parameter. On exactly the same ground we show that the variances of the charm quarks are large and they display a jump at the critical point for a first order phase transition. Thus this quantity, similarly to the lifetime of the J/Ψ, behaves

exactly as an order parameter and could give important informations about not only the transition to the QGP but also to the order of the phase transition, i.e. first, second order or simply crossover to the QGP. Of course since D particles are the lighest charmed meson they are most easily produced in heavy ion collisions thus they are the best probes for the phase transition.

An important ingredient of our approach is a constraint to satisfy the Pauli principle. The approach, dubbed Constrained Molecular Dynamics (CoMD) has been successfully applied to relativistic and non-relativistic [4, 5] heavy ion collisions and plasma physics as well [6].

We use molecular dynamics with a constraint for a Fermi system of quarks with colors. The color degrees of freedom of quarks are taken into account through the Gell-Mann matrices and their dynamics are solved classically, in phase space, following the evolution of the distribution function.

In our work, the quarks interact through the Richardson's potential $V(\mathbf{r}_i, \mathbf{r}_j)$:

$$V(\mathbf{r}_{i,j}) = 3 \sum_{a=1}^{8} \frac{\lambda_i^a}{2} \frac{\lambda_j^a}{2} \left[\frac{8\pi}{33 - 2n_f} \Lambda(\Lambda r_{ij} - \frac{f(\Lambda r_{ij})}{\Lambda r_{ij}}) \right], (1)$$

and[7]

$$f(t) = 1 - 4 \int \frac{dq}{q} \frac{e^{-qt}}{[\ln(q^2 - 1)]^2 + \pi^2}. \tag{2}$$

λ^a are the Gell-Mann matrices. We fix the number of flavors $n_f = 2$ and the parameter $\Lambda = 0.25$ GeV,$(\hbar, c = 1)$ unless otherwise stated. Here we assume the potential to be dependent on the relative coordinates only. The first term is the linear term, responsible for the confinement, the second is the Coulomb term [7].

We solve the classical Hamilton's equations:

$$\frac{d\mathbf{r}_i}{dt} = \frac{\mathbf{p}_i}{E_i}, \tag{3}$$

*Email: terranova@lns.infn.it; zhou@lns.infn.it; bonasera@lns.infn.it

$$\frac{d\mathbf{p}_i}{dt} = -\overrightarrow{\nabla}_{\mathbf{r}_i} U(\mathbf{r}). \tag{4}$$

Initially we distribute randomly the quarks in a box of side L in coordinate space and in a sphere of radius p_f in momentum space. p_f is the Fermi momentum estimated in a simple Fermi gas model by imposing that a cell in phase space of size $h = 2\pi$ can accommodate at most g_q identical quarks of different spins, flavors and colors. $g_q = n_f \times n_c \times n_s$ is the degeneracy number, n_c is the number of colors (three different colors are used: red, green and blue) hence $n_c = 3$; $n_s = 2$ is the number of spins[1].

A simple estimate gives the following relation between the density of quarks with colors, ρ_{qc}, and the Fermi momentum:

$$\rho_{qc} = \frac{3n_s}{6\pi^2} p_f^3 \tag{5}$$

We generate many events and take the average over all events in each cell on the phase space. For each particle we calculate the occupation average, i.e. the probability that a cell in the phase space is occupied. To describe the Fermionic nature of the system we impose that average occupation for each particle is less or equal to 1 ($\bar{f}_i \le 1$).

At each time step we control the value of the average distribution function and consequently we change the momenta of particles by multiplying them by a quantity ξ: $P_i = P_i \times \xi$. ξ is greater or less than 1 if $\bar{f}_i$ is greater or less than 1 respectively; which is the *constraint* [5]. Details of the model are discussed in [3]. Here we illustrate the case with $m_u = 5$ MeV, $m_d = 10$ MeV and cut-off to the linear term of $2fm$ [3] which has been introduced to avoid numerical uncertainties. Such a system displays a clear first order phase transition at high baryon densities. The results are completely analogous for the other parameter sets discussed in [3].

After our system of u and d quarks has evolved to its equilibrium configuration, we insert one J/Ψ, i.e. c $\bar{c}$ quarks and let them evolve. The Pauli principle is responsible for the kinetic energy of the light quarks. The Fermi motion increases for increasing densities. On the other hand the embedded charm quarks do not see the Pauli principle because they are different Fermions. However, there is a strong interaction among all the quarks given by the Richardson potential. Because of such interaction, the charm quarks start to exchange energy with the surrounding medium and finally get in equilibrium with the other quarks. Thus c quarks are a perfect probe of the system since they can wander anywhere in the available phase space of the system. In particular we can calculate the variance for instance of the charm quarks. For a non interacting Fermi gas, the variance in momentum space is given by

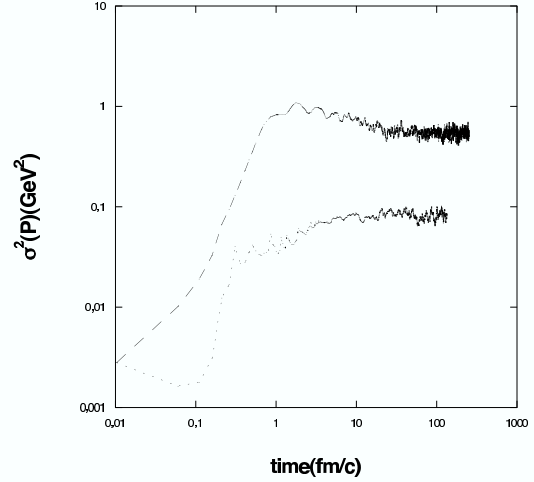$$\sigma^2 = <p^2> - <p>^2 = \frac{3}{80} p_F^2 \tag{6}$$

FIG. 1: Time evolution of momentum variances of charm quarks at two densities, above and below the QGP phase transition.

similar relations can be obtained for kinetic energy fluctuations. Of course, because of the interaction, the fluctuations are larger than our estimate and might spectacularly increase near a phase transition.

In fig.(1), we plot the variance in momentum space vs time for two densities above and below the critical point for a first order phase transition. One immediately sees that variances are much larger than our estimate for a Fermi gas (here respectively $\sigma^2 = 0.0055$ and $0.0328 GeV^2$ for the cases diplayed in fig.1) given above because of the strong interaction. Initially the variance of the c quarks are very small, but after a transient time, fluctuations are transferred from the light to the heavy quarks up to a stationary value. As expected the variances are larger above the phase transition, i.e. at high density.

This is clearly demonstrated in figure (2) where the energy density, the order parameters, the J/Ψ lifetime [3] and the variances are plotted versus density. All quantities jump at the critical point signaling a first order phase transition. In order to show that these properties are independent on details of the forces and that the charm quarks are real good probes of the phase transition, we have arbitrarily increased of a factor 2 the interaction strenght between the c$\bar{c}$ quarks alone. This results in a change of the J/Ψ lifetime (squares in fig.2) but the jump of its lifetime at the critical point remains.

In order to see what could happen in realistic heavy ion collisions we have performed some calculations in a transport model at $\sqrt{s} = 200 GeV$. We have used the JPCIAE code which includes Pythia as a generator of elementary collisions [8] and performed calculations for
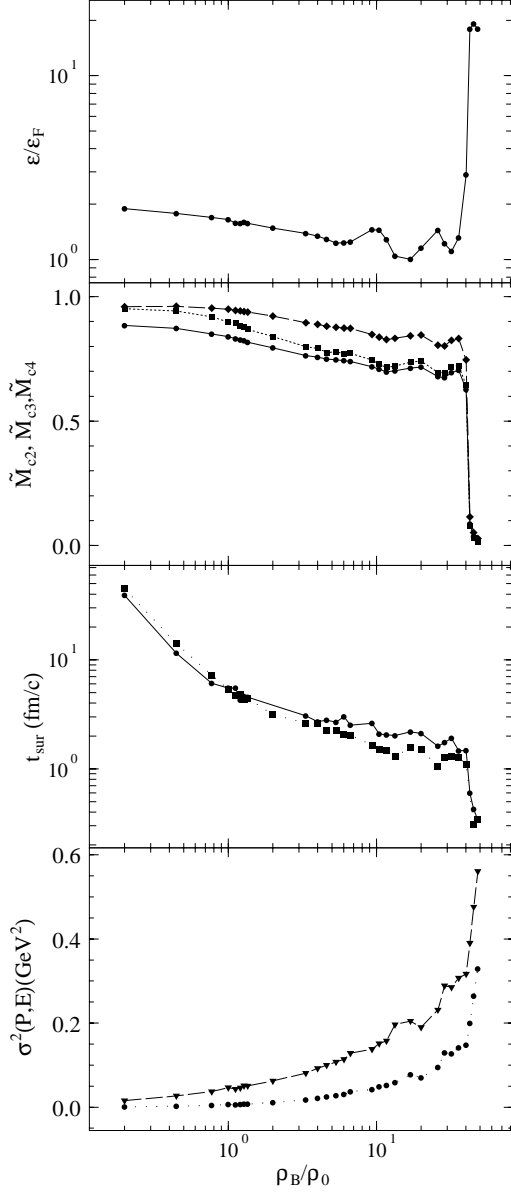
FIG. 3: Variances (circles) and transverse minus rest mass (triangles) vs mass number of the colliding nuclei. Full symbols refer to D-meson production while open symbols refer to pions.

In the same graph we have plotted the transverse mass minus the rest mass of the particle(triangles), which gives an indication of the degree of equilibration reached. The full symbols refer to D-mesons while the open symbols refer to pions. As expected such variances are roughly a constant i.e. independent of the mass number for colliding ions heavier than oxigen. Infact, this is an expected result since the model contains in principle no phase transition to the QGP. Thus normalizing the variance say in Au+Au respect p+p collisions at the same beam energy should give about 1. An anomalous increase from such a value should indicate that much more physics than contained in our transport code is indeed at play. Furthermore, some anomaly in the variances with increasing mass number of the colliding nuclei should give a clear indication to the occurrence of the phase transition and, possibly, of its order. This is so because we expect no QGP for small systems while a transition should occur for relatively large nuclei. How large those nuclei should be at RHIC beam energy could be obtained from the analysis we propose in figure(3). In the same figure we have plotted the average transverse kinetic energy for open charms and pions. Such a quantity should give an indication of the degree of equilibration of the system. As it can be easily seen the latter quantity has a similar behaviour of the variance which is what we expect if the system is equilibrated. Indeed one can see that there is a proportionality between the two quantities especially for colliding nuclei heavier than oxigen, furthermore the average kinetic energies for different particles are very close which is another indication of thermal equilibrium. Looking at the pions results only, it seems that equilibrations is reached already for small systems such as d+d. This is so because many pions are produced in an event and also, pions are produced in different steps of the collision.

FIG. 2: Energy density (top panel), normalized order parameters (2nd panel), time survival of J/ψ (3rd panel) and variances in momentum and kinetic energy of c quarks (bottom panel) versus density divided by the normal density ρ_0, for $m_u = 5$ MeV, $m_d = 10$ MeV and cut-off$= 2fm$.

symmetric nucleus-nucleus collisions starting from pp to AuAu. Variances in the transverse momenta of produced open charms are calculated for central collision (impact parameter b=0fm). In figure (3) we plot the variances versus sum of the mass numbers of the colliding nuclei. The variances are calculated averaging over the events which contain at least one D meson produced (circles).
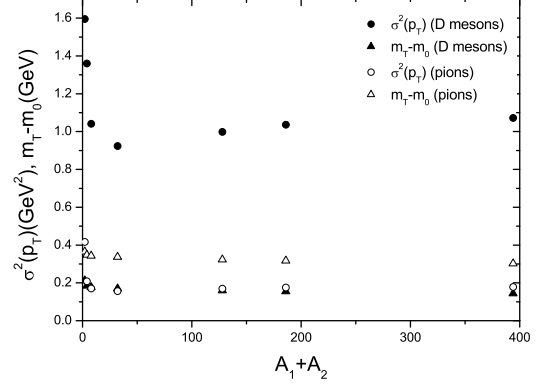
This results in smaller variances than the one obtained for D-mesons already in our kinetic approach. Thus pions could give an indications on the temperature reached in the reaction, while a phase transition could be signaled by the possible J/Ψ suppression or the large fluctuations of the D-meson which might be a stronger signal since they are more abundantly produced in the collisions. In this context, large fluctuations are understood compared to the pp case.

In conclusion, in this work we have discussed a semi-classical molecular dynamics approach to infinite matter at finite baryon densities and zero temperature starting from a phenomenological potential that describes the interaction between quarks with color. Pauli blocking, necessary for Fermions at zero temperature, is enforced through a constraint to the average one body occupation function. We have studied the case of a set of parameters which displays a first order phase transition at high baryon densities. We have shown that, similarly to the order parameter and the J/Ψ lifetime, the variances in momentum space of charm quarks 'jump' at the critical point of the phase transition. We have proposed an experimental search at RHIC inspired by the CoMD results. In particular we have simulated heavy ion collisions in a transport model (which does not include a phase transition), at fixed beam energy and changing the mass numbers of the colliding system. We have shown that already for small colliding nuclei such as oxigen the system could reach thermal equilibrium. An anomalous behavior of the variances of the open charms transverse momenta as a function of the mass number of the colliding system should give a signal for the transition to the QGP. In particular variances for pp collisions should be much smaller than those obtained in Au+Au collisions at the same beam energy if there is a phase transition. If not, we expect variances to be in agreement to our estimate in fig.(3). If the large fluctuations are found in open charms production, then the phase transition could be further studied by changing the beam energy and/or the impact parameter selection for a given system and energy, since we expect a phase transition for central and not for the most peripheral collisions.

Acknowledgements

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